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Is there a compact companion orbiting the late O-type binary star HD 164816?

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ABSTRACT

We present a multi-wavelength (X-ray, γ-ray, optical and radio) study of HD 164816, a late O-type X-ray detected spectroscopic binary. X-ray spectra are analyzed and the X-ray photon arrival times are checked for pulsation. In addition, newly obtained optical spectroscopic monitoring data on HD 164816 are presented. They are complemented by available radio data from several large scale surveys as well as the *FERMI* γ-ray data from its *Large Area Telescope*. We report the detection of a low energy excess in the X-ray spectrum that can be described by a simple absorbed blackbody model with a temperature of $\sim$ 50 eV as well as a 9.78 s pulsation of the X-ray source. The soft X-ray excess, the X-ray pulsation, and the kinematical age would all be consistent with a compact object like a neutron star as companion to HD 164816. The size of the soft X-ray excess emitting area is consistent with a circular region with a radius of about 7 km, typical for neutron stars, while the emission measure of the remaining harder emission is typical for late O-type single or binary stars. If HD 164816 includes a neutron star born in a supernova, this supernova should have been very recent and should have given the system a kick, which is consistent with the observation that the star HD 164816 has a significantly different radial velocity than the cluster mean. In addition we confirm the binarity of HD 164816 itself by obtaining an orbital period of 3.82 d, projected masses $m_1 \sin^3 i$ = 2.355(69) M$_\odot$, $m_2 \sin^3 i$ = 2.103(62) M$_\odot$ apparently seen at low inclination angle, determined from high-resolution optical spectra.

Key words: stars: neutron, stars: individual: HD 164816, stars: individual: 2XMM J180356.8-241845.

1 INTRODUCTION

The expected total number of Neutron stars (NSs) in our Galaxy is predicted to be 10^8-10^9 (Narayan & Ostriker 1990) of which isolated NS should form the majority. Until today there are ~2000 known radio pulsars and only seven known isolated thermally emitting NS (INS) called the Magnificent Seven (Haberl 2007, Kaplan et al. 2011). Since the discovery of the first INS (RX J1856.5-3754) in 1996 (Walter et al. 1996) the search for more thermally emitting NSs is an ongoing process. Those seven objects have been recognized by their high X-ray to optical flux ratio and their rather soft X-ray emission represented by low X-ray hardness ratios. Thus looking for objects with similar properties is one way to find new candidates, see e.g. Pires et al. (2009). It is clear that many candidates can be missed, for example when they are harbored in binary or multiple star systems, since the X-ray flux is dominated by the host star, or as compact companions to runaway stars (Posselt et al. 2008). Searches for Pulsar companions around OB runaway stars have been performed by Philp et al. 1996, Sayer et al. 1996.

We search for X-ray pulsations from all X-ray sources near or identified with galactic OB stars, in search of non-interacting (and hence effectively isolated) NSs that remain bound in a stellar system following the supernova. About 10% of such systems remain bound after the first supernova (Kuranov et al. 2009).

HD 164816 is located in the direction of the young open cluster NGC 6530. Prisinzano et al. (2005) recently investigated in depth the distance of this cluster: Literature values range from 560 pc (Loktin & Beshenov 2001) to 2000 pc (Walker 1957, van den Ancker et al. 1997). The mean of the distance estimates (in table 1

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of Prisinzano et al. (2005) and the value found by Prisinzano et al. (2005) themselves, 1250 pc) is 1543 ± 345 pc, which we now use in this paper; all but one (560 to 711 pc, Loktin & Beshenov 2001) values found in the literature are consistent with this value within 1 σ. Within 1 σ, our value is also consistent with the distance of $\sim$ 1250 pc obtained by Prisinzano et al. 2005.

HD 164816 itself is located at α = 18h 03m 56.866s and $\delta = -24°18'45.22''$ and has V=7.09 mag (Reed 2003). Recently, Megier et al. (2009) determined the distance towards HD 164816 by interstellar Ca II absorption to be 864 ± 136 pc. Hence, the distances of the NGC 6530 cluster and the star HD 164816 are deviant by 1 to 2 σ, which may indicate that HD 164816 is somewhat foreground to the cluster, to be discussed below.

The region around it is also known as the Lagoon Nebula (NGC 6523 = M 8) which is one of the brightest HII regions in the Galaxy where star formation has started a few 10^7 yrs ago (van den Ancker 1997). However, the membership of HD 164816 is uncertain.

NGC 6530 has about 2000 known members which display an age gradient (Damiani, Prisinzano, Micela & Sciortina 2006). From March 2001 to July 2003 HD 164816 has been in the field of view of seven X-ray observations, one with *XMM Newton* and six with the Chandra X-ray observatory (*CXC*).

In the following we will present the X-ray spectral and temporal properties from *XMM PN* and *Chandra ACIS-I* data indicating a compact companion candidate (§2). We present the orbital parameters of the spectroscopic binary O-type star in §3. Then we present the available radio survey data as well as the analysis of γ-ray data obtained by *FERMI's* Large Area Telescope (*LAT*) in §4. A discussion of the physical nature of the possible companion will be given in §5 and concluding remarks will be made in §6.

2 X-RAY DATA ANALYSIS

We report here on the spectral and temporal analysis of the X-ray source 2XMM J180356.8-241845 that is coinciding with the optical position of HD 164816 and has been found by our search for pulses in X-ray sources near galactic O-type stars.

We extracted events from the archived pipeline produced *XMM PN* data (see table 1) in a circular region with a radius of 30 arcsec around the centroid of 2XMM J180356.8-241845 located approximately 3.1 arcmin from the pointing of the observation by using the XMM Science Analysis System (SAS) version 10. As background we extracted events in a nearby source free region of similar size. We used only single-pixel event types for the spectral analysis as well as for the performed source detection in the first energy band of *XMM-Newton* (0.2 - 0.5 keV) as there are known calibration issues. Event types higher than single-type are known to result in an elevated soft X-ray background which is most prominent in the reported first energy band[1].

Extracting the background region is a somewhat complicated task as the field is very crowded and contaminated by several fringes. Although the thick filter was in place in the *XMM* Observation, those might result from incomplete blocking of UV/optical light coming from the 5th magnitude star 9 Sgr (see Fig.1) or possibly originating from stray light of the nearby Low Mass X-ray binary (LMXB) GX 9+1 (Langmeier, Sztajno, Trümper & Hasinger 1985) around 1 deg outside the field of view (fov). Checking the background light curve of this observation we could not identify any times of elevated background and thus can use the whole observation time as a good time interval. Nevertheless we also investigated the spatial distribution of the arriving photons in the background extraction region and could not find any significant concentration, rather a homogeneous distribution (see inset in Fig.1 left panel).

The *Chandra* observations do not show any fringes or an otherwise enhanced background as the threshold for optical contamination is $V \sim 3.1$ for the used ACIS-I detector[2] (HD 164816 has V=7.09). Hence, the chosen background regions are not contaminated by any source or fringe.

2.1 Spectral Analysis with *XMM Newton*

As a first step we have re-analyzed the X-ray spectrum of 2XMM J180356.8-241845. Its spectral properties have already been reported in Rauw et al. 2002 where they performed an X-ray population study on an *XMM Newton* observation and among other things conclude that the X-ray emission of HD 164816 is typical for an O9.5 III-IV star. However, they did not take the low energy part of the spectrum from 0.2 - 0.5 keV into consideration.

Trying to reproduce their results we first re-analyzed the *XMM PN* dataset of ObsID 0008820101 carried out with the thick filter in use and centered at 9 Sgr.

As a following step Response and Anxillary files have been computed by using the XMMSAS tasks RMFGEN and ARFGEN. The data then have been grouped by a minimum of 20 counts per energy bin in order to minimize the scattering of data points. After background subtraction there are 961 net source counts available. Including as well the first *XMM Newton* energy band (0.2 - 0.5 keV) in the spectral fit by using a warm absorbed MEKAL plasma (Mewe et al. 1985, Kastra 1992) results in an unsatisfying fit of χ^2_ν equal 1.57 with 34 d.o.f which is not in agreement with what Rauw et al. 2002 have found (i.e. χ^2_ν=1.08 in 0.5 - 5 keV). By looking at the spectrum we clearly notice an excess in the range 0.2 - 0.5 keV that cannot be modeled by the used absorbed MEKAL plasma model. In addition we recognize some feature around 0.3 keV but we ignored data at the energy range 0.27 to 0.32 keV as there is a drastic dip in the effective area of the *EPIC PN* detector in that energy range.

We have carried out a source detection in the energy range 0.2-0.5 keV in order to exclude an artificial nature of the detected low energy excess. This energy part is believed to be mostly from the possible compact companion and has not been regarded by Rauw et al. (2002). We detected 2XMM J180356.8-241845 in this energy range with a detection maximum likelihood of L ~235 with $L = -\ln p$ where p is equal to the probability that the detected signal was generated by a random fluctuation. Since we only took single-pixel events into consideration we can rule out that the excess is due to elevated background. As the given likelihood value for the source detection can be considered significant we conclude that the excess is of real nature (see right panel in Fig.1). A source detection in the energy range 2.0 to 10 keV leads to a null detection, hence the source is soft. Improving the fit by blindly adding a blackbody component could not be achieved thus we decided to use a more sophisticated approach. Therefore we tried to subtract the MEKAL component from the spectrum.

[1] Please see document XMM-SOC-CAL-TN-0068 on http://xmm2.esac.esa.int/external/xmm_sw_cal/calib/documentation/index.shtml for reference

[2] Please see the most recent *Chandra* proposers guide, vers 14.0 December 2011 for reference

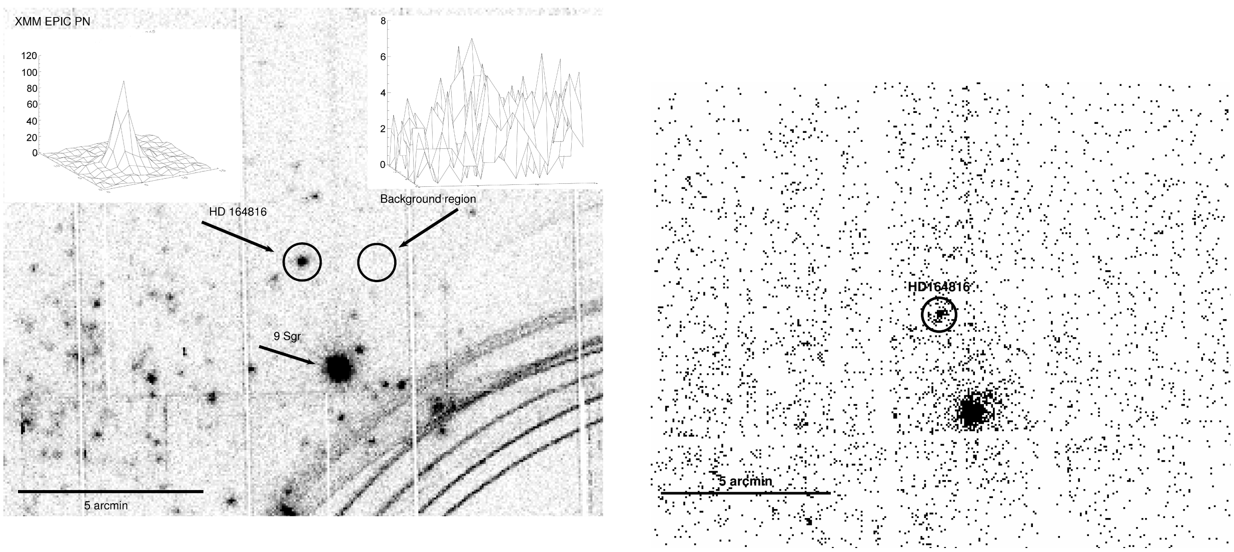

Figure 1. *Left Panel*: Image showing a 17×14 arcmin^2 close-up view of the EPIC PN observation centered at the position of HD 164794 (9 Sgr) in the energy range 0.2 - 10.0 keV. Shown are the position of HD 164816 with the circle indicating the 30 arcsec extraction region together with the background extraction region. As well seen is the rather large contamination by other sources in the field and the contribution of fringes from the optical emission of 9 Sgr. In addition surface plots of the extracted source (left inset) and background regions (right inset) are shown. *Right Panel*: Here we show HD 164816 in the energy range 0.2-0.5 keV with only single events displayed.

Table 1. X-ray observation log of the used *XMM-Newton* and *Chandra* observations

Observation ID	Pointing	Start Time	exposure time (ks)	Detector	offset from HD 164816 (arcmin)
	XMM-Newton				
0008820101	HD164794 (9 Sgr)	2001-03-08 11:21:27	23.572	MOS1/2, PN	3.07
	Chandra				
3754	M8	2003-07-25 17:27:12	129.600	ACIS-I	4.27
4397	M8	2003-07-24 10:07:26	14.820	ACIS-I	4.27
4444	M8	2003-07-28 00:00:07	30.190	ACIS-I	4.27

In order to eliminate the thermal plasma component we used XSPEC (version 12.6) to simulate an absorbed MEKAL plasma in the energy range 0.5-2.0 keV as there is negligible information in the range 2.0-10.0 keV. As an input the best fit parameters for temperature and absorption reported in Rauw et al. 2002 were used. Afterwards this simulated spectrum is used to create a fake data set with the same exposure time, background, response and anxillary files as used for the observation of HD 164816. The faked data are grouped according to the *EPIC PN* data (i.e. a minimum of 20 counts/bin). This grouped MEKAL spectrum is then used as background for the observation in order to subtract the contribution of the thin plasma model.

Visually checking the produced spectrum confirms the MEKAL component to be consistent with zero. The remaining excess is fitted with an absorbed blackbody model which leads to a best fit temperature of around 53.7 eV that now serves as an initial input for the future complete analysis. As a next step the entire spectrum is fitted with an absorbed thin plasma model plus the blackbody

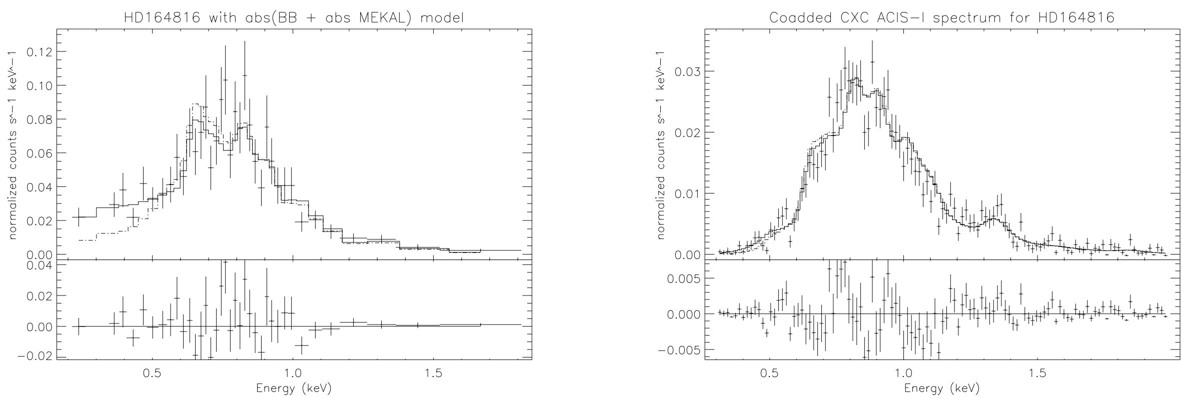

Figure 2. *Left Panel*: Shown here is the best fit absorbed blackbody plus MEKAL model (continuous line) to the *XMM PN* data together with the residuals for a blackbody temperature of kT$_{bb}$ ~48.79 eV. Data points from 0.27 keV to 0.32 keV are not taken into consideration in the fit due to the drastic dip in the effective area around 0.3 keV. The dash-dotted line represents the best fit absorbed MEKAL model to the data and one can see the already mentioned excess from 0.2 to 0.5 keV. *Right Panel*: The coadded *Chandra ACIS-I* observations are shown here together with the best fit absorbed blackbody + MEKAL plasma model and their corresponding residuals for a blackbody temperature of kT$_{bb}$ ~49.85 eV. Likewise the dash-dotted line represents the best fit absorbed MEKAL model, where the excess from ~0.3 to ~0.5 keV becomes visible.

component by iteratively fixing and freeing the parameter pairs for the blackbody and MEKAL plasma model (i.e. pairs of temperature and normalization) which lead us to a best fit blackbody temperature of $52.36^{+7.78}_{-4.86}$ eV with $\chi^2_\nu = 1.06$.
As the interstellar column density derived by Diplas & Savage 1994, $0.15^{+0.05}_{-0.04}\cdot10^{22}$ cm^{-2}, is significantly smaller than the value derived by our fit ($0.40^{+0.03}_{-0.05}\cdot10^{22}$ cm^{-2}) we decided to introduce a second systemic absorption component. Such a systemic absorption was already suggested by Rauw et al. 2002 and could possibly be attributed to a stellar wind. By introducing such a component we can put tighter constraints on the errors of the individual parameters and get an interstellar absorption of $0.08^{+0.07}_{-0.03}\cdot10^{22}$ cm^{-2} which is consistent with the one found by Diplas & Savage 1994. The resulting blackbody temperature is $48.79^{+4.01}_{-8.65}$ eV (see Fig.2). Values for the systemic absorption and MEKAL temperature are $0.32^{+0.09}_{-0.10}\times10^{22}$ cm^{-2} and 0.24±0.02 keV respectively. The absorbed flux in the energy range 0.2-2.0 keV of 1.08×10^{-13} erg cm^{-2}s^{-1} is found to be higher than the presented value for the energy range 0.5-5.0 keV by Rauw et al. 2002. For completeness we have computed as well the unabsorbed flux in the 0.2-2.0 keV range (2.89×10^{-13} erg cm^{-2}s^{-1}). In addition we have used the blackbody model normalization to give an estimate on the radius of the emitting area. Using a distance of 864±136 pc results in a radius of the (circular) emitting area of 7.14±1.12 km which is in the range of a NS (see Hohle et al. 2012). Adopting the same distance range we used the MEKAL normalization to give an estimate on the emission measure (EM) of HD 164816, which turns out to be $3.93\pm0.10\times10^{54}$ cm^{-3}. Those values are typical for O9V single stars (see e.g. Bhatt et al. 2010 and Nazé et al. 2011). An overview of the most important parameters can be found in table 2.

2.2 Spectral Analysis with *Chandra*

HD 164816 has been in the field of view of six *Chandra* observations of which we unfortunately had to exclude two as the high energy transmission grating (HETG) was in place and HD 164816 thus not covered by the active part of the detector. The remaining four observations (ObsIDs 977, 3754, 4397, 4444; see table 1) taken by the Advanced CCD Imaging Spectrometer in Imaging mode (ACIS-I) have been reprocessed individually, as follows. First we extracted events in a circular region around HD 164816 with a radius of 10 arcsec for each observation and as there are neither any fringes nor any other signs for an elevated background present we arbitrarily chose one background field per observation with a radius of 20 arcsec in a source free region in close proximity to HD 164816. We chose a somewhat bigger extraction region for the background as the background level of *Chandra* observations is in general very low.
Response and Anxilary files have been created afterwards for source and background regions each by using the CIAO (version 4.2) tools MKRMF and MKARF. As we noticed that the source counts are low in the single observations we inspected the effective area of each observation and found the differences for ObsIDs 3754, 4397 and 4444 to be indistinguishable and hence combined these three event files. However for ObsID 977 we find the effective area to be significantly smaller and thus did not include this observation. Coadding the remaining three observations lead to a total effective exposure time of ~172 ks with 1203 counts available for HD 164816 and thus having slightly higher statistics compared to the *XMM* observation.
For the following spectral analysis we applied the same methods and constraints as to the *XMM PN* observation but we used the C-statistic instead of χ^2 in that case. As a best fit blackbody temperature we get $49.85^{+1.29}_{-8.75}$ eV with $C = 168.77$ for 109 d.o.f. in the energy range of 0.3-2.0 keV (see Fig.2 right panel), as the ACIS-I detector is only calibrated from 0.3 to 11.0 keV. Comparing the MEKAL plasma temperature and both absorption components obtained from the *Chandra* data with the values from *XMM PN* data we note that they are in agreement. This is also true for the values of the MEKAL plasma temperature in the Rauw et al. 2002 analysis. The computed absorbed and unabsorbed flux are 1.19×10^{-13} erg cm^{-2}s^{-1} and 2.19×10^{-13} erg cm^{-2}s^{-1} respectively. Computing the radius of the emitting area 864±136 pc we end up with R$_{emit}$ = 7.07±1.11 km which is consistent with the value derived from the XMM fit. By using the MEKAL normalization factor we find the EM in the range $3.76\pm0.09\times10^{54}$ cm^{-3}, which is similar to the

Table 2. Spectral parameters inferred from fitting the *Chandra* and *XMM-Newton* spectra of HD 164816.

Model [a]	χ^2 / $C-$stat	D.O.F.	interstellar n_H / systemic n_H (10^{22} cm^{-2})	kT_{MEKAL} (eV)	kT_{BB} (eV)	R_{emit} (km)	f_X (0.2-2.0 keV) (10^{-13} erg cm^{-2} s^{-1})
			XMM-Newton	(0.2 - 2.0 keV)			
abs*MEKAL	χ^2 = 53.30	34	$0.35^{+0.08}_{-0.07}$	$237.81^{+19.61}_{-11.48}$	—	—	7.90
abs(BB+ abs*MEKAL)	χ^2 = 32.84	31	$0.08^{+0.07}_{-0.03}$ / $0.32^{+0.09}_{-0.10}$	$237.81^{+23.44}_{-19.68}$	$48.79^{+4.01}_{-8.65}$	7.14±1.12	2.89
Model [a]	χ^2 / $C-$stat	D.O.F.	interstellar n_H / systemic n_H (10^{22} cm^{-2})	kT_{MEKAL} (eV)	kT_{BB} (eV)	R_{emit} (km)	f_X (0.3-2.0 keV) (10^{-13} erg cm^{-2} s^{-1})
			Chandra	(0.3 - 2.0 keV)			
abs*MEKAL	184.68	112	$0.39^{+0.01}_{-0.02}$	$227.70^{+10.40}_{-5.06}$	—	—	1.01
abs(BB+ abs*MEKAL)	168.77	109	$0.09^{+0.11}_{-0.09}$ / $0.28^{+0.09}_{-0.16}$	$238.90^{+12.52}_{-10.77}$	$49.85^{+12.92}_{-9.56}$	7.07±1.11	2.19

[a] BB = blackbody; MEKAL = hot diffuse gas model based on Mewe et al. 1985, 1986, Kaastra 1992 and Liedahl et al. 1995

XMM data.
We summarize our X-ray results in Table 2.

2.3 X-ray pulsation search with *XMM Newton*

We performed a periodicity search at the position of 2XMM J180356.8-241845. For performing the pulsation search only the *XMM Newton* observation has been reprocessed as the *EPIC PN* detector was used which is the only available instrument for this source with a sufficiently short readout time (73 ms in that configuration). In particular there are 1284 arrival times in this set that have been searched for a periodic signal by means of the bayesian approach developed by Gregory & Loredo 1992 for the detection of a signal with unknown shape. Applying this method leads to a detection of a signal at $9.7804^{+0.0007}_{-0.0003}$ s (see Fig.3) with a probability that the data favor a periodic model over a constant model to be 0.56. This resulting period could afterwards be reproduced by applying the Z^2_m test with m being the number of harmonics (Buccheri et al. 1983) in the period range 1 to 10s with a stepsize equal to the independent fourier spacing (IFS) i.e. 1/T_{span}. This number of harmonics has been optimized by using the H-Test (De Jager, Swanepoel & Raubenheimer 1989) and was found to be maximized for m=1. The resulting Z^2_1 value is equal to 22.67 at a period of $9.7813^{+0.0005}_{-0.0007}$ s with the number of expected peaks exceeding that Z value to be 5.25×10^{-6}. The given errors are 1 σ errors. Finally a pulsation search with a method based on the cash statistic (Cash 1979) as described in Zane et al. (2002) has been applied to the arrival times and could determine the period to be 9.78±0.06 s (again in the range 1 to 10s and using the IFS). The errors are again at the 1 σ level.

Hence, the period found by the bayesian method, being the proper choice for this kind of data as it uses an unbinned approach, is confirmed by the cash and Z^2_1-test. In addition we have created a simulated data set of equal length in exposure time with 1284 randomly distributed photons. Applying the Z^2_1-Test and the cash-test to that set of data lead to no detection at ~9.78 s. Furthermore the most likely periods found by those two tests in the faked data set are not in accordance ($P_{Z^2_1}$ ~5.15 s and P_{cash} ~1.12 s).

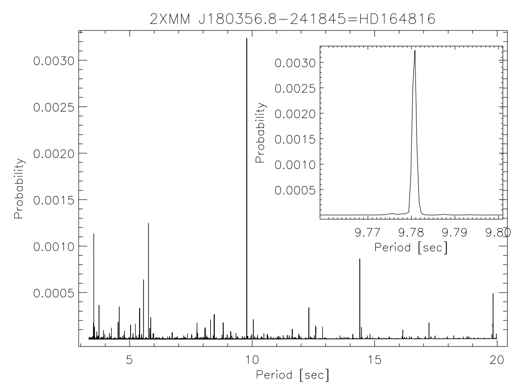

Figure 3. Here we show the periodogram of the detected ~9.78 s pulsation for the X-ray source identified with HD 164816 found by the bayesian approach with *XMM Newton*.

The CXC ACIS-I data sets although improving the number of source photons have not been used for timing analysis as the ACIS frame time is ~3.24 s and thus too long to significantly detect such a period.

The phase-folded X-ray light curve for 2XMM J180356.8-241845 in the energy range 0.2-2.0 keV has a pulsed fraction of 60.4±15.4 % (c.f. Fig.4). As a final step we extracted arrival times for the brightest X-ray source in the field of view (i.e. the O4 star 9 Sgr) in the energy range 0.2-2.0 keV which results in 18769 counts. We folded the created light curve with the obtained period which results in a constant non-periodic signal. This is likewise true for the extracted background region, again in the energy range 0.2-2.0 keV. Considering this non-periodic signal of the background and of 9 Sgr, we conclude that the observed period in HD 164816 is not due to some background modulations caused for example by the readout time or multiples of it.

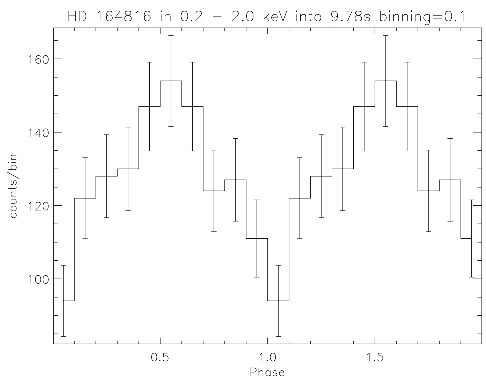

Figure 4. In this figure we show the phase-folded light curve for the X-ray source in the energy range 0.2-2.0 keV folded into the resulting best period of 9.78 s resulting from *XMM Newton* data. For clarification we show two full cycles with a binning of 0.1.

Both the soft excess and the ∼10 s pulsation would be typical for a NS in the system assuming that it will not be interacting with its host star and can hence be treated as effectively isolated (see Haberl 2007 for typical periods of thermally emitting isolated NS), namely ∼3 to ∼11 s.

3 ORBITAL PARAMETERS OF HD 164816

3.1 Optical data analysis

Optical échelle spectroscopy of HD 164816 has been obtained at two observatories in Chile: the Cerro Armazones Observatory (OCA, about 20 km east of the Paranal Observatory) and at the Cerro Tololo Interamerican Observatory (CTIO).

Optical spectroscopy at the OCA was secured using the Bochum Echelle Spectrographic Observer (BESO) fiber-fed from the focus of the 1.5m Hexapod Telescope (see Fuhrmann et al. 2011). Fifteen spectra were obtained between 2009-04-21 and 2010-03-28 covering the wavelength range of 3530 - 8860 Å with a spectral resolution of R = 50000 (Fuhrmann et al. 2011) (see Table 3). The data were reduced using dedicated scripts written under MIDAS. The reduction includes overscan, bias and flatfield correction; individual échelle orders were extracted, wavelength calibrated and normalized to the continuum. Finally, cosmic spikes have been removed. The cleaning was complicated by the fact that most He and H lines contain narrow (and variable) emission features. Moreover, for each night there is just one exposure. Wavelength calibration has been improved using telluric bands close to 6900 and 7600 Å and the spectrum of η CMa as a template. The improved radial-velocity system is stable to about 100 m/s. The zero point of the radial-velocity system was checked by measuring the IAU standard star HIP 910, which is a slow rotator, in 6 nights. The average radial-velocity is 14.16±0.13 km/s which is in good agreement with 14.4±0.9 km/s found by Evans (1967).

Optical spectra at the CTIO were obtained using the high dispersion optical Blanco échelle spectrograph fiber-fed from the 1.5m SMARTS telescope. Fourteen spectra taken between 2010-07-25 and 2010-09-14 cover the range from 4820 - 7120 Å (see Table 3). The R ≈20000 spectra were extracted using software written

Table 3. Journal of spectroscopic observations of HD 164816 obtained at the CTIO and OCA observatories

Spectrum	HJD 2 400 000+	Exp. [sec]	Spectrum	HJD 2 400 000+	Exp. [sec]
OCA_20090414	54936.8391	1800	OCA_20100328	55284.8365	1500
OCA_20090421	54943.8225	1800	CTIO_20100725	55403.7934	200
OCA_20090508	54960.8685	1800	CTIO_20100728	55406.7316	300
OCA_20090707	55020.8242	1800	CTIO_20100731	55409.6988	300
OCA_20091010	55115.5480	1800	CTIO_20100804	55413.6327	300
OCA_20091018	55123.5011	1800	CTIO_20100805a	55414.6293	300
OCA_20091020	55125.5094	1800	CTIO_20100805b	55414.7672	300
OCA_20091024	55129.5112	1800	CTIO_20100812a	55421.6210	600
OCA_20091025	55130.5172	1800	CTIO_20100812b	55421.7031	600
OCA_20091027	55132.5113	1800	CTIO_20100820	55429.6515	400
OCA_20100321	55277.9383	1500	CTIO_20100904	55444.5716	600
OCA_20100323	55279.9109	1500	CTIO_20100907	55447.5156	600
OCA_20100324	55280.8909	1500	CTIO_20100908	55448.5887	600
OCA_20100325	55281.8479	1500	CTIO_20100909	55449.5630	600
OCA_20100327	55283.8057	1500	CTIO_20100914	55454.5746	600

in IDL [3]. The orders are traced using the cross-dispersed flat images. The spectrum is extracted using a boxcar extraction, as is the flat spectrum. The spectrum is then divided by the extracted flat spectra. In general we obtained 3 spectra at each epoch. These are scaled, median-filtered to reject cosmic rays, and summed. Wavelength calibration is based on a Th-Ar calibration lamp exposure taken just prior to each stellar observation. The zero-point of the wavelength scale is uncalibrated at the level of 1 pixel (3 km/s). No attempt has been made to convert to a flux intensity scale.

Although the zero point of the radial-velocity system is uncertain, there is very good agreement between the systemic (mass-center) velocity obtained separately from the individual datasets (OCA and CTIO data).

Optical spectra of HD 164816 do not contain many features (see Fig. 5): in addition to the interstellar lines there are only lines of the Balmer series and those of neutral and ionized helium and possibly faint lines of CII, CIII, Si IV, and O II. In the OCA data forbidden lines, e.g., [OIII] at 5006.84 Å, are also visible, most likely residual features from the M8 nebular emission remaining after the background subtraction. The Balmer series lines (and also some He I lines) show narrow and variable nebula emission lines always at the same wavelength (e.g. 5876 Å(see Fig. 6)).

Our new spectra confirm the binarity (Penny 1996, Howarth et al. 1997, Mason et al. 2009) of the system (see Fig. 6). We extracted the Doppler information and determined the spectroscopic orbit[4]; we used nine spectral regions centered at sufficiently strong He I/II lines ($\lambda\lambda$ 4024/4026, 4387, 4471, 4686, 4713, 4923, 5016, 5875, 6678 Å). The strong forbidden line [OIII] 5006.84 Å has been removed prior to the fitting (visible mainly in the OCA data).

The global modeling of the data included orbital parameters (P, e, ω, T_0, V_0, $K_{1,2}$), relative intensities ($I_{1,2}$) and projected rotational velocities of the components ($v_{1,2} \sin i$); see Table 4 for the individual parameters. Prior to the fit all emission seen in He lines has been cleaned "manually" in order to secure a proper determination of the radial-velocity. The fitted spectrum consisted of the sum of two appropriately broadened and Doppler shifted synthetic spectra for each orbital phase. Theoretical rotational profiles (see Gray, 1976) were computed assuming a linear limb darkening law and solid-body rotation. For T_{eff} = 32500 K, $\log g$ = 4.00 [log(cm s^{-2})]

[3] http://www.astro.sunysb.edu/fwalter/SMARTS/ech_proc.txt

[4] In the case of the CTIO spectra only 4923 Å, 5016 Å, 5875 Å, 6678 Å lines were covered

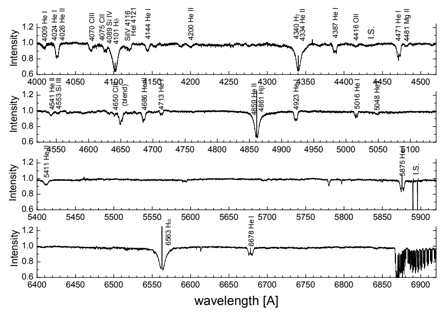

Figure 5. Average spectrum of all OCA observations on HD 164816 with line identifications (I.S. stands for interstellar band/line)

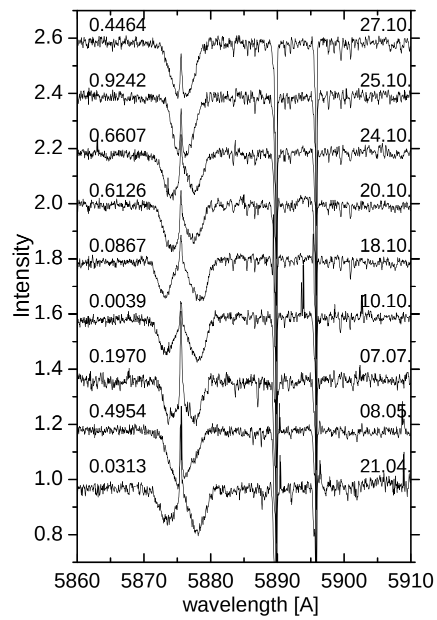

Figure 6. The He I 5876 Å line profile changes with the orbital revolution of the binary while the interstellar neutral sodium doublet ($\lambda\lambda$ 5893, 5896Å) is not following the orbital revolution. The same holds for the narrow nebula emission at 5876 Å HeI, which is variable in strength but constant in wavelength, i.e. radial velocity. The dates of observations (in 2009) and orbital phases (counted from the periastron passage) are also shown.

and the wavelength range of the modeled He lines the linear limb darkening coefficient is $0.20 < u < 0.28$ (see van Hamme, 1993). Because the shape of the rotational profile depends on the limb darkening only slightly, an average value of $u = 0.24$ was used. The template high-resolution synthetic spectrum taken from the Pollux database [5] corresponding to $T_{eff} = 32500$ K, $\log g = 4.00$ and solar metallicity provided a very good fit to the data. Synthetic spectra corresponding to higher temperatures showed helium lines being partially in emission. On the other hand, a synthetic spectrum corresponding to 30000 K resulted in smaller equivalent widths for the helium lines as observed. It is also possible that the helium abundance is higher than assumed in the synthetic spectra while the temperature is slightly lower. Previous determinations of the spectral type of HD164816 are mostly B0V (see e.g. Morris 1961). Our spectroscopy indicates O9V or O9.5V as the best estimates.

In the first step we tried to find the approximate orbital period for the system using the full width at half maximum changes of the strong He I line at 5875 Å. The present set of 29 spectra spanning 17 months indicated only one possible orbital period, $P \sim 3.82$ days. First fitting experiments, however, showed it was impossible to satisfactorily fit all the data without the assumption of a fast apsidal motion. Hence we added $d\omega/dt$ to the parameter set with ω_0 valid for the periastron passage T_0 (at an arbitrarily selected epoch of the binary).

Because the long-term All-Sky Automated Survey (ASAS[6]) light curve (Pojmanski, 1997 & 1998) does not show eclipses, a constant relative intensity of the components throughout orbital phases has been assumed. The best global fit to 29 spectra and 9/4 (OCA/CTIO) spectral regions resulted in (among other parameters) $P = 3.81932(39)$ days and $e = 0.232(16)$. The reduced $\chi^2 = 1.394$ indicates a small inconsistence of the model and the fitted spectra. The larger χ^2 very probably arises from the simple assumption of spherical shapes for the components and also variations in the continuum rectification level.

The resulting projected masses of the components $m_1 \sin^3 i = 2.31(17)$ M$_\odot$ and $m_2 \sin^3 i = 2.10(16)$ M$_\odot$ indicate a low inclination angle for the system, which is supported by the lack of eclipses. The ZAMS mass of an O9.5V star (X = 0.70, Y = 0.28, Z = 0.02; see Claret 2004) is about 16 $M_\odot$; the ZAMS radius is about 5 R$_\odot$ (at the cluster age of 2.3 Myr (Prisinzano et al. 2005) the star would have a corresponding radius of about 5.6 R$_\odot$). Then the inclination angle would be 30 - 35°. Assuming $i = 30°$and $a \sin i = 16.8(2)$ R$_\odot$ we get a semi-major axis of 33.6(4) $R_\odot$. In the case that the components are rotating synchronously (the synchronization time scale is usually two orders of magnitude shorter than circularization time scale; see e.g., Pan et al. 1998) their radii (using $v_{1,2} \sin i$) are then $R_1 = 13.2$ R$_\odot$ and $R_2 = 12.1$ R$_\odot$, indicating that both components already left the main sequence or that they are still rotating asyn-

[5] http://pollux.graal.univ-montp2.fr/

[6] Please refer to http://www.astrouw.edu.pl/asas/

Table 4. Spectroscopic elements inferred from fitting the 29 OCA/CTIO spectra. The 1σ error of the last digit is given in parentheses. Reduced χ^2 is given

Parameter		
P	[days]	3.81932(39)
e		0.232(16)
ω_0	[rad]	-0.97(7)
V_γ	[km s^{-1}]	-77.1(13)
K_1	[km s^{-1}]	109.4(26)
K_2	[km s^{-1}]	120.3(30)
T_0	[HJD]	2 455 000.88(3)
$d\omega/dt$	[rad/yr]	0.67(7)
U	[yr]	9.4(11)
I_1		0.536(14)
$v_1 \sin i$	[km s^{-1}]	85.4(28)
I_2		0.463(14)
$v_2 \sin i$	[km s^{-1}]	79.9(32)
$m_1 \sin^3 i$	[M$_\odot$]	2.31(17)
$m_2 \sin^3 i$	[M$_\odot$]	2.10(16)
$a \sin i$	[R$_\odot$]	16.8(2)
χ^2_r		1.394

The following elements were optimized: P - period, e - eccentricity, ω_0 - longitude of periastron passage at T_0, V_0 - systemic velocity, $K_{1,2}$ - semi-amplitudes of radial velocity changes, T_0 - time of the periastron passage, $d\omega/dt$ - apsidal motion rate (U is apsidal-motion period), $I_{1,2}$ - relative intensities of spectra, $v_{1,2} \sin i$ - projected rotational velocities of components. Projected masses of the components, $m_{1,2} \sin^3 i$, and projected major axis, $a \sin i$ are also given

chronously (with rotation factors $F_{1,2} \sim 2$). Without knowledge of the inclination angle and in the view of possible asynchronous rotation of the components determination of the true radii and masses is also complicated.

3.2 Distance

The individual distance towards HD 164816 was determined by Megier et al. (2009) from interstellar Ca II absorption to be 864 ± 136 pc, while the NGC 6530 cluster is at 1543 ± 345 pc (see Sect. 1). Since these two values are deviant by more than 1 σ, we will discuss the distance of HD 164816 and whether it is or was a member of the NGC 6530 cluster.

Since the radii of the two O9.5 stars in HD 164816 could not be determined directly by us, we cannot compute the distance by the Stefan-Boltzmann law from temperature, radius, and luminosity. However, since the two stars are located close to the dwarf sequence (V), we can compute the distance modulus from the apparent magnitude of HD 164816 (corrected for both extinction and binarity) and the typical absolute magnitude of an O9.5V star.

The published magnitudes of HD 164816 are (all in mag from Simbad and references therein) U = 6.22, B = 7.09, V = 7.09, I_C = 6.99, J = 7.006, H = 8.053, and K = 7.072 (BV from Hipparcos, U from Reed et al. 2003, I Cousins from Rauw et al. 2002, JHK from 2MASS, Cutri et al. 2003), all having small errors of roughly ±0.01 mag for UBVI and ±0.025 mag for JHK.

Using the intrinsic UBVI$_C$JHK colors of an O9.5V star according to Bessell et al. (1998) for temperatures of 31250 ± 150 K and $\log g = 5.0$ (for main sequence dwarfs), we can obtain the extinction by comparing the apparent and intrinsic colors; for the interstellar extinction law, we interpolate in each band according to Cardelli et al. 1989, Savage & Mathis 1979, and Rieke & Lebofsky 1985. Then, we obtain $A_V = 1.10 \pm 0.05$ mag as interstellar extinction towards HD 164816.

For the total bolometric luminosity of an O9.5V star, we use the latest determination from Hohle et al. (2010) using Hipparcos distances and extinction corrections from Hipparcos BV and 2MASS JHK colors, all corrected for multiplicity, interpolating between O9V and B0V. For the bolometric correction, we use again Bessell et al. (1998) for temperatures of 31250 ± 150 K and $\log g = 5.0$ (for main sequence dwarfs), namely B.C.$_V$ = 3.025 ± 0.085 mag.

Then, we obtain as (main-sequence spectro-photometric) distance towards HD 164816 the value 1030 ± 230 pc. This value is consistent with the value by Megier et al. (2009) from interstellar Ca II absorption being 864 ± 136 pc, Hence, our assumptions appear justified. For O9IV, O9V, B0IV and B0V stars, the values lie between 890 ± 40 pc and 1240 ± 140 pc, i.e. are consistent within the errors with the O9.5V case. In the case of the latter distance, the evidence for HD 164816 to lie in front of the cluster, would be much weaker.

We conclude that HD 164816 may lie up to a few hundred pc in front of the NGC 6530 cluster. However, we cannot exclude that the star is located inside or at the front of the cluster. The peculiar radial velocity (corrected for Galactic rotation and solar motion using a local standard of rest of $(u, v, w)_\odot = (10.4, 11.6, 6.1)$ km/s (Tetzlaff et al. 2011)) of HD 164816 is $v_{r,pec} = -80.7^{+5.0}_{-4.4}$ km/s whereas for NGC 6530 it is $v_{r,pec} = -7.9^{+3.5}_{-9.1}$ km/s (Kharchenko et al. 2005). Hence, HD 164816 appears to move towards us relative to the NGC 6530 cluster. The difference between the two velocities is 72.8 ± 7.9 km/s. While the radial velocity difference indicates that the star is now moving towards us relativ to the cluster, it can still be located inside or at the front edge of the cluster. If the system includes a neutron star born in a supernova, this supernova should have given the system a kick, which may have been the cause for the discrepant radial velocity. Given that the most massive and earliest star in this cluster (9 Sgr) has a spectral type of O4, the progenitor of the neutron star in HD 164816 has to have had an even earlier spectral type and, hence, had a life-time of below 3 Myr. Given that this is comparable to the cluster age (2.6 Myr), the presumable supernova should have happened very recently and the system HD 164816 therefore cannot be located much foreground to the cluster. The proper motion of HD 164816 actually agrees with the typical proper motion of the NGC 6530 cluster.

3.3 X-ray longterm variability

As we have discovered a ~3.81 d orbital period we searched the available X-ray data sets mentioned in §2 for any longterm variability; in particular those are three *Chandra* and one *XMM-Newton* set.

For this purpose we first derived the absorbed fluxes for *XMM-Newton* and *Chandra* observations (see §2.1 and §2.2) and plotted them vs the starting time of each observation taken from table 1. As there is only very limited statistics in each of the three *Chandra* exposures, we merge them and use the starting time of the middle observation. As a result one can see that the fluxes are consistent within the error bars. We have as well investigated the longterm behavior of the individual *Chandra* count rates, which cannot be compared to the *XMM-Newton* count rate as their instrumental responses are different. We cannot find any variation in those count rates as well. Thus the merging of the datasets is justified. We hence

cannot detect the ~3.81 d orbital period in the available X-ray observations.

4 RADIO AND γ-RAY OBSERVATIONS

In order to get a complete view of the multiple system HD 164816 we have searched as well for any significant detection in the available radio data catalogs. We could neither detect it in the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS) nor by the GTEE 35 MHz Radio survey carried out by the low frequency T-array near Gauribidanur, India. Some feature could be detected in the H I All-Sky survey, the CO galactic plane survey and the 4850 MHz Survey carried out by the Parks and Green Bank Radio observatories. Due to the rather large pixel scales of around one degree, 0.1 degree and 0.02 degree respectively we consider the detected feature unlikely to be associated with HD 164816. In addition HD 164816 with a galactic latitude of ~ -1° is lying quite close to the galactic plane and the detected radio emission is hence more likely to come from diffuse emission of interstellar gas.

With the *FERMI* γ-ray telescope now in orbit we took as well data obtained by its *Large Area Telescope (LAT)* at the position of HD 164816 into consideration. As the whole sky is monitored every six hours for a bit more than two years now we analyzed data taken over this whole range (from 2008 Aug 04 to 2010 Aug 09) in order to get the highest possible statistics. Events in the energy range from 600 MeV to 300 GeV have been chosen and have been filtered for galactic and extra galactic diffuse γ-ray emission. A likelihood analysis has been carried out afterwards which serves as a source detection since the photon statistics at the position of HD 164816 are still very low. For this purpose spectral models for all sources in a ROI of ten degrees radius around HD 164816 have been accounted for contribution and were modeled simultaneously. A super exponential cutoff powerlaw has been assumed for HD 164816 which is typical for γ-ray emitting neutron stars (c.f. Trepl et al. 2010). Carrying out the likelihood analysis yielded no significant detection of the source.

5 DISCUSSION

The X-ray source associated with HD 164816 shows X-ray pulsations at ~ 9.78 s and in addition a soft X-ray excess with a blackbody temperature of ~ 49 eV both consistent with a compact companion (NS) in the system. Further optical observations confirm that HD 164816 is a spectroscopic binary consisting of two O9V or O9.5V stars that are in a tight orbit of ~ 3.82 days.

Accreting neutron stars and generally neutron stars in high-mass and supergiant X-ray binaries have in common that they emit at higher energies than 2 keV, but in the EPIC PN observation we did not detect any signal at above 2 keV, so that we can exclude an accreting pulsar as the source for the X-ray emission.

All the aforementioned scenarios have in common that the NS is emitting non-thermal radiation that can be fitted by a powerlaw or Bremsstrahlung-model and is thought to occur from the accretion process (either Roche-lobe overflow or wind accretion). Constant mass accretion can in fact be ruled out in the case of HD 164816 as the detected soft X-ray emission excess from 2XMM J180356.8-241845 can be described by a pure blackbody model which means we observe thermal emission from the NS surface itself. In addition, evolutionary considerations based on standard formulae (Lipunov 1992), demonstrate that the stage of accretion is improbable taking into account the spin period of the NS and the parameters of the binary. Without better knowledge about the separation of the NS from the O-stars it is impossible to make clearer statements, but at a few Myr the NS is either in the ejector, or in the propeller stage.

The orbital separation between the compact companion and the binary system must be at least around 100 $R_\odot$ as empirical studies show that a tighter system is dynamically unstable unless the separation of the compact object from the binary center of masses is about three to five times larger than the semi-major axis of the binary system for an eccentricity of ~ 0.2 (Moriwaki & Nakagawa 2002) i.e. $\geqslant$ 51 to 85 $R_\odot$ here. Therefore wind accretion is negligible as the orbital separation is large.

The other possible nature of the compact companion to HD 164816 might be a White Dwarf (WD) as the detected temperature of ~ 50 eV (5.80×10^5 K) would place the object in the somewhat overlapping region of WDs as Super-Soft X-ray sources (SSS) in Be/X-ray binaries (Kahabka et al. 2006) and thermally emitting NS.

However as the typical age of a WD should be $\gtrsim$ 1 Gyr the accompanying O-stars with masses of around 18 $M_\odot$ and 20 $M_\odot$ respectively would have already evolved and exploded.

The compact companion lying just by chance in the line of sight of HD 164816 cannot be ruled out yet as the available *Chandra* observations are only spread by a few days (see Table 1). This is too short to significantly detect any separation between the centroid of the soft and hard component of the X-ray spectrum.

If this detection is a chance projection, then the most probable candidates are radio pulsars. The probability for chance alignment of a neutron star within the point spread function (PSF) of the X-ray source can be estimated as follows: Neutron stars can be detected as either X-ray, γ-ray or radio pulsars if they lie above the so-called dead-line in the P - $\dot{P}$ diagram; they reach this dead-line at an age of roughly 10 Myr (despite according to general cooling curves a NS may cool down to the temperature of ~50 eV at the age of ~5×10^5yr); if there are 5×10^8 neutron stars in the Galaxy (at ages up to 12 Gyr), then there are roughly 3×10^5 neutron stars detectable as either X-ray or radio pulsars (~ 2000 of them are known). Then, given the PSF of the Chandra source (full width at half maximum 3.70 ± 1.60 arcsec) or the PSF of the XMM source (full width at half maximum 4.19 ± 1.78 arcsec) and the area of the whole sky, we obtain a probability for a chance alignment, between HD 164816 and a NS of 5 to 7×10^{-4}. However, the direction of these *XMM* and *Chandra* pointings is not random, but towards an OB cluster, where the probability for a NS is higher: According to Hohle et al. (2010), the area on the sky where almost all SNe are expected (inside OB associations), is 35 % of the total sky. The probability for chance alignment of a NS in the *XMM* and *Chandra* PSF is then 2 to 3×10^{-4}, still very low. Even if we restrict the estimate to the densest OB clusters close to the Galactic plane, the estimate would be less than one order of magnitude higher, so that the probability of chance alignment would still be below 1 %. Given that this estimate is very low, we have a large probability for the potential NS not to be a chance alignment, but to be related to HD 164816. This suggests that a NS is related to HD 164816.

O stars are generally not known to have soft X-ray blackbody excesses. It has been shown by Nazé 2009 that those stars are in general emitting spectra that can be fitted best with single or multi component MEKAL models with temperatures starting at ~0.2 keV.

A scenario that involves colliding winds instead of a compact com-

panion can be considered as well as HD 164816 consists of a close binary. However such a model would require a Raymond-Smith thermal plasma with a temperature of kT ~ 0.6 keV (Oskinova 2005) or a hard non-thermal X-ray component (De Becker et al. 2004). Taking a look at the MEKAL temperature of ~ 0.2 keV in the case of HD 164816 we note that it is almost a factor of three lower. In addition the spectrum is missing any component that can be fitted by a non-thermal model as the spectral counts from 2 keV on are consistent with zero. Hence, the NS does not appear to be accreting.

As seen from §4 HD 164816 is not significant at radio wavelengths; this might have implications for the colliding wind scenario (De Becker et al. 2004), but that is beyond the scope of this paper.

Assuming a distance 864±136 pc we compute the X-ray luminosity to $L_X \sim 2.58\times10^{31}$erg s^{-1}. Together with a bolometric luminosity for a O9.5V star from Hohle et al. (2010) this yields $\log(L_X/L_{Bol})$ = -6.73 which is in agreement with the relation for O stars found by Berghöfer et al. (1997) (c.f. Fig. 4 therein). In the case of colliding winds this ratio should however be higher than the given value (see e.g. De Becker et al. 2004). It seems thus rather unlikely to get the low energy excess from colliding wind interaction. A similar conclusion was reached by Rauw et al. (2002), where they state that regarding the L_X/L_{Bol} ratio no evidence for an increased value is found.

Like Rauw et al. (2002) we find a higher than average interstellar absorption (see table 2) which can be attributed to circumstellar or nebula material. This should result in strong suppression of the spectrum in the energy range 0.2 - 0.5 keV. In contrast to this we find an excess in that range on top of the absorption. Hence an additional source outside the region of circumstellar material responsible for that is highly probable. This is consistent with the earlier conclusion that the separation of the probable NS has to be at least 100 $R_\odot$.

Emission line features in the X-ray spectrum as described in van der Meer et al. (2005) are not detected and as well not expected as such a phenomenon is only common in HMXBs and SGXBs. Those cases can be excluded as they both involve accretion processes which are not seen in our case.

If there is a pulsating NS within the X-ray PSF and if this NS is not orbiting the O star of HD 164816, then it could be an isolated NS in the NGS 6530 cluster. A pulsation period of some 10s is not atypical for isolated young to intermediate-age NS - as e.g. the Magnificent Seven with pulsation periods of few to some 10s (see e.g. Haberl 2007).

6 CONCLUSION

We found peculiarities in the X-ray, optical, and kinematical data of HD 164816:

- There is a soft excess in the X-ray spectrum of both XMM and Chandra.
- The radius of the emitting (circular) area related to the soft excess would be ~7 km.
- There is an indication of 9.78 s pulsation in the XMM data (not detectable with Chandra due to low timing resolution of the used ACIS-I detector (~3.24 s) and small count rate).
- If HD 184816 includes a neutron star born in a supernova, this supernova should have given the system a kick, which is consistent with the fact that the star HD 164816 has a significantly different radial velocity than the cluster mean.

All those four observational indications would be consistent with a compact object like a neutron star in the system orbiting the spectroscopic binary HD 164816 at a larger separation. A NS should have soft X-ray emission. A neutron star of few Myr age isolated from the other stars without accretion can have a period of few to 10 s (like the Magnificent Seven neutron stars). If there is a NS in the system, there should have been a supernova in the system before. Such a supernova could introduce a kick velocity to the neutron star born in the supernova. If the neutron star remained bound to the close spectroscopic binary, they would now all move away fast relative to their birth cluster.

We did not find any evidence for X-ray emission due to colliding winds. An accreting neutron star would show hard X-ray emission, which was not found. Hence, if there is a neutron star in the system it is effectively isolated (and non-accreting) from the O-type star.

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